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Prospective energy needs in Mediterranean offshore aquaculture: Renewable and sustainable energy solutions

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ABSTRACT

Offshore aquaculture industry is considered among the fastest growing industries worldwide. However, further expansion of this industry requires larger breeding installations positioned even further from shore. These installations inevitably would require substantial automation powered by appropriate energy sources. Thus, this paper investigates appropriate sustainable renewable energy generation solutions to meet anticipated needs. Firstly, an account of energy requirements of a typical offshore aquaculture installation is presented to realise the scale of energy required. Subsequently, current status of solar, wind, wave and current renewable energy technologies is given and their applicability for Eastern Mediterranean offshore aquaculture is investigated. Finally, further challenges and research milestones to overcome are discussed.

Contents

1. Introduction

Current World population is 6.8 billion, and it is expected to pass through the 7 billion mark in 2012. According to the UN, the world population in 2050 will be 9.1 billion – a rise of over 6.6 billion in the 100 years since 1950 [1]. The question naturally arises

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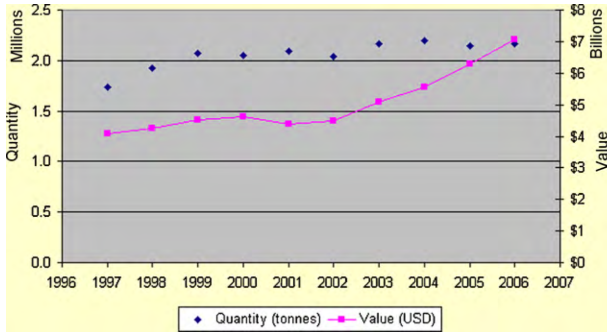

Fig. 1. European aquaculture production in tones and value in US dollars [3].

is whether Earth can cope with so many people. Do we have the natural resources to feed this rising World population?

European Union and other leading Nations have long realised the need to develop a robust offshore aquaculture industry as a means to satisfy increasing food needs of a rising World population. European aquaculture industry has grown, in a relatively short time, from a 'cottage' industry to become a dynamic European and Global sector providing a valid alternative to captured fisheries and supplying products to satisfy consumers' demand [2]. As shown in Fig. 1 during 2006 European aquaculture (fish, crustaceans, molluscs, etc.) production alone climbed at 2 million tones, turning it into a 7 billion dollar industry [3].

European and National policies encourage increase of offshore aquaculture sector as a means to provide healthy seafood at affordable prices [4]. However, competing use of shallow coastal waters for other industrial uses, such as tourism, prohibit substantial growth of offshore aquaculture industrial sector. Furthermore, although in 1994 60% of Europe's needs for seafood were coming from within its resources by 2005 this position had reversed [2]. The satisfaction of Europe's as well as world's needs, are primary fulfilled from the production reared in the developing countries, especially from Asia which accounts for roughly 91.4% of the global production share [5].

An answer is sought in placing offshore aquaculture installations even further from shore. This approach has a number of inherent technical problems relating among others to feeding of cultured stock and monitoring. Development of large scale offshore aquaculture installations will inevitably include significant automation applied to feeding systems and monitoring. These applications have substantial energy requirements. In the case of offshore aquaculture installations, positioned significantly away from shore, energy generation has to take place on sites [6].

Energy generation from renewable energy sources, such as solar, wind, wave or current, is a sustainable mean to meet energy requirements. Selection of particular renewable energy source depends on individual farm characteristics such as wind, solar, and current potential. To meet this aim, several issues need to be resolved, such as housing of equipment to protect against salinity and moisture and design of supporting structures to withstand cyclic loading of sea waves. In addition, power storage is of paramount importance in Renewable energy generation since renewable potential tends to be periodically available.

Thus, this paper presents the forthcoming energy needs of a typical offshore aquaculture installation and investigates how renewable energy sources could be used to meet these energy needs. In particular, it gives an account of anticipated energy requirements of a typical offshore aquaculture installation to realise the scale of an energy standalone system required. Subsequently, current status of solar, wind, wave and current renewable energy technologies is given and their applicability for Eastern Mediterranean offshore aquaculture is investigated. Finally, further challenges and research problems to overcome are listed.

2. Offshore aquaculture industry in Eastern Mediterranean

Aquaculture economic activity can take place (a) on land using fresh water or sea water (recirculation systems), (b) in protected coastal areas or (c) offshore. However, due to competing claims for coastal land and coastal shallow waters future solutions are sought in offshore aquaculture installations. Offshore aquaculture involves farming in an offshore environment of sea organisms such as finfish, mollusks, crustaceans and aquatic plants. Unlike harvesting of wild fish, aquaculture involves cultivating aquatic populations under controlled conditions. Numerous aquatic animals and plants are currently farmed, including salmon, seabream, seabass, shrimp, catfish, trout, abalone, oysters and seaweed. Commercial aquaculture supplies currently account for one half of the fish and shellfish directly consumed by humans [7].

Potential benefits of offshore aquaculture can be among others (a) increase of aquatic food production, (b) reduce reliance on wild fish stocks, and (c) moving facilities offshore may reduce impacts on sensitive coastal habitats. However, potential negative consequences of offshore aquaculture can be among others: (a) waste may lead to increased pollution, (b) high rates of parasites in farmed fish could lead to infection of wild fish, (c) surrounding habitat may be altered, (d) farmed animals and plants may be introduced into surrounding habitat, and (e) aquaculture may require wild-caught fish as food for farmed fish and as starting stock [8].

Although a fledgling industry, a range of cage systems is now potentially available for offshore aquaculture in the Mediterranean. However, not all of these may prove to be effective in the intended environmental conditions and production regimes [9]. The prevailing structure types of offshore cages can fall into the following: (a) floating flexible, (b) floating rigid, (c) semi-submersible flexible, (d) semi-submersible rigid, and (e) submersible rigid. During the past few years, the floating flexible type (see Fig. 2) is the predominant type in Eastern Mediterranean due to its proven robustness in extreme weather scenarios. Another categorisation of offshore aquaculture structures can be presented based on mooring type however for the purposes of this research thesis categorisation by structure type was found to be the most appropriate.

To realise the scale of such installations, typical round flexible cages can accommodate up to 200,000 fingerlings (70–80 tonnes

Fig. 2. Offshore aquaculture installations utilizing flexible round cages positioned in South coast of Cyprus.

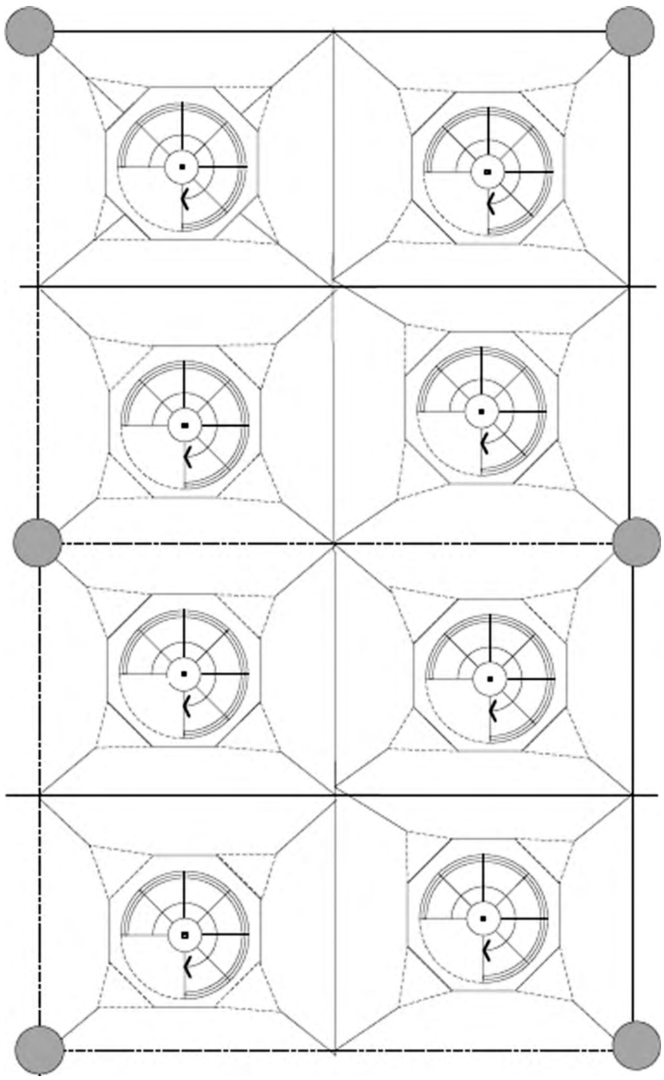

Fig. 3. Typical arrangement of aquaculture cages in "side by side" cages.

mature fish stock). However, smaller cages occasionally are used to accommodate up to 100,000 fingerlings to enable smooth development of production plan. Since fish is a live commodity, at its maturity it cannot be stored in a warehouse. It needs feeding and subsequently significant cost realisation [10]. Thus, "just-in-time" production is of paramount importance. Taking into account a two year turn-around of each cage, a typical Eastern Mediterranean offshore aquaculture installation normally accommodates 20–30 cages, i.e. a 750–1000 annual tonnage yield. Fig. 3 above gives a rough illustration of typical aquaculture cages' arrangement. This arrangement has proven over the years to have numerous advantages relating to feeding and harvesting operations and mooring grid robustness. Typical columns can have of up to five or six dual cage rows. Thus, a typical farm is expected to have a couple cage columns consisted by dual cage rows. Thus, this arrangement would ultimately govern sensor positioning and sensor density and subsequently projected energy needs.

Up to this day the energy needs in terms of electricity or fuel for electricity production of an offshore aquaculture installation although relatively small in relation to other industries, they are vital for smooth and uninterrupted operation. The choice of the power source is defined by a list of rational but sometimes subjective parameters such as distance from shore, in terms of grid connected systems and initial cost of equipment and installation of small generators, in terms of standalone systems [11]. Other decision affective factors could be the convenience of operations, cost and ease of maintenance and of course safety of the power generating system [11]. In the case of powering an installation with a standalone generator the choice of a power source is a choice between electric motors (or batteries) and internal combustion engines. Although the former is self-explanatory the latter may include diesel, gasoline, natural and liquefied petroleum gas (LPG) engines, with diesel being the most common [11].

3. Prospective energy needs of an offshore aquaculture installation

Automation needs in an offshore aquaculture installation can fall within two main categories, namely, (a) automated feeding and (b) remote monitoring. In the case of the first category highly sophisticated systems have been developed by different manufactures [12]. However, these automated feeding systems have substantial energy and housing requirements but can among others monitor fish population and feed distribution, record various environmental parameters and schedule feeding time intervals accordingly. Current uses of these feeding systems include onshore positioning of the main hardware usually applied to farms in fjords (Norway) or coastal protected areas (Greece, Turkey).

Furthermore, to meet the needs of offshore applications, mobile versions of these automated systems have been developed in the form of feeding barges. These barges have been specifically developed to serve multiple installations simultaneously by bringing fish feed onsite, managing its distribution and at the same time providing all necessary personnel accommodations and meet equipment spatial requirements [12]. However, these feeding barges require substantial financial investment and running costs.

In the case of remote monitoring a wide variety of specialized sensors and tools have also been developed that monitor and record various environmental parameters and facilitate fish stock maturation. These parameters significantly affect an offshore aquaculture unit's operations governing its efficient production and ultimately its profitability. The following sections illustrate how these environmental parameters and specialized tools can affect an offshore aquaculture unit's operations. For the purpose of this research thesis, the case of single column – dual row cage is considered, comprised of eight cages (see Fig. 3). As mentioned before, a typical Eastern Mediterranean offshore aquaculture installation consists of at least a couple of such columns.

3.1. Underwater lighting

Underwater lighting at offshore aquaculture cages can reduce fish maturation increase growth and improve feed utilisation [13]. The most important benefit from their usage is prolonged feeding periods since fish can consume fish feed during night. Thus, overall fish breeding cycle can significantly be reduced. The need for such tool is considered to be one kit per cage and therefore for the purposes of this research paper eight kids were considered.

3.2. Feeding monitoring

Fish feed accounts for around 60% of total cost of offshore aquaculture units [2]. Thus, feeding motoring is of the outmost importance relating to overall profitability of any aquaculture farm. Various means have been developed to monitor feeding including among others feed blowers connected to various sensors such as feeding cameras and pellet sensors.

3.2.1. Feeding camera

Feeding camera provides visual control of the feeding process in cages [14]. This camera typically hangs stationary just underneath the fish' eating area (typically at 5–8 m) and looks straight up to easily detect uneaten pellets sinking towards the camera. One camera is usually permanently installed in each cage. Thus, for the purposes of this research paper eight feeding cameras have been considered.

3.2.2. Pellet sensor

Similar to feeding camera, pellet sensor aims to provide better feeding monitoring to offshore aquaculture installations. This sensor is installed at the bottom of a pellet collector funnel, below the fish' main eating area and uses Infra-Red single beam optics to spot uneaten pellets. The IR Pellet Sensor system is suspended 5–8 m below the fish' eating area within the cage. Even small pellets down to 1–2 mm will be detected [15]. Thus, similar to feeding cameras, for the purposes of this research paper eight pellet sensors have been considered.

3.3. Surveillance

An ever increasing threat to offshore aquaculture installations, as offshore aquaculture economic activity prevails, is the hostile visits of unwanted visitors (e.g. local fishermen) or predators (fish eating birds). Thus, for better offshore operations monitoring, surveillance cameras can be used. These surveillance cameras can then be connected to a remote video system to provide information relating to offshore installations when staff is not present or in bad weather. For the case of a single column of eight double row cages, four surveillance cameras can be considered, positioned at the four edges of the column.

3.4. Current sensors

Knowledge of prevailing sea currents at offshore installations can prevent feed waste. Strong sea currents can take way fish feed before fish stock has the opportunity to consume it. This sensor can be located at a strategic position in the offshore aquaculture installation and can be connected to the rest of the sensors' grid.

3.5. Oxygen sensor

Cultured fish stock at low oxygen levels can lose its appetite and stop consuming fish feed. Low oxygen levels can primarily occur due to poor status of cage nets. Using oxygen sensor in combination with current and temperature readings give a good picture of the fish' environment and its capability to consume fish feed. Thus, for the purposes of this research paper eight oxygen sensors can be considered to be installed at each fish aquaculture cage.

3.6. Wireless cage sensor

This piece of equipment allows connection of all aforementioned sensors and surveillance cameras and the collected data are wirelessly transmitted from each cage to the land base. Thus, this is an integral part of the system providing communication between cages and the onshore base [16].

3.7. Remote video

In addition to the wireless connection to the onshore base, this piece of equipment provides the opportunity for live images from each cage being transmitted via internet to home, office or another farm. It provides full remote access to all cameras installed at the farm, such as surveillance-, surface- and underwater cameras, including zoom, pan/tilt and winch controls. To meet this end a PC with a broadband internet connection is needed to enable live video transmission from the offshore aquaculture installation [17].

3.8. Aggregation of energy requirements

Following hardware needs presented above, this section estimates anticipated daily usage of each piece of equipment in order to aggregate respective power needs. Thus, for a single column of four dual cages, eight underwater lights, eight feeding cameras, four surveillance cameras, one current sensor, eight pellet sensors, eight oxygen sensors, one wireless cage kit, and one remote video kit were considered. Using expert opinion, the anticipated hourly usage per day was estimated, leading to the respective power needs determination as shown in Table 1.

4. Renewable and sustainable energy solutions to meet prospective energy needs in Eastern Mediterranean offshore aquaculture

Renewable energy sources provide a sustainable alternative to offshore aquaculture installations' ever increasing energy needs. However, combination of renewable energy solutions varies considerably depending on the geographical characteristics of the position of application, such as solar irradiation levels, wind potential and sea current potential. Thus, this section presents the case of Eastern Mediterranean and in particular Cyprus investigating the potential applicability of alternative renewable energy solutions. Finally, areas for further research are identified applied to this type of economic activity.

4.1. Solar irradiation levels

Mediterranean basin is well known for its high levels of solar irradiation and the high levels of penetration of photovoltaic (PV) technology. Average daily irradiation exposure in Cyprus varies between 9.8 h in December and 14.5 h in June [18]. Similarly, as suggested by Fig. 4, adopted from the website of the Photovoltaic Geographical Information System (PVGIS) the cumulative yearly PV solar electricity potential for Cyprus varies between 1800 and 2000 KWh/m^2 solar irradiation and using a 0.75 conversion rate, a

Table 1
Hardware selection, anticipated daily usage and respective power needs [12].

A/A	Equipment	Unit(s)	Power/unit (W)	Total power (W)	Daily use (h)	Wh/Day
1	Underwater lights	8	115	920	4	3680
2	Feeding camera	8	1.2	9.6	2	19.2
3	Surveillance camera	4	30	120	8	960
4	Current sensor	1	0.9	0.9	2	1.8
5	Pellet sensor	8	1.44	11.52	2	23.04
6	Oxygen sensor	8	0.24	1.92	2	3.84
7	Wireless cage sensor	1	6	6	12	72
8	Remote video	1	3	3	8	24
	Sum	39	157.78	1072.94	40	4783.88

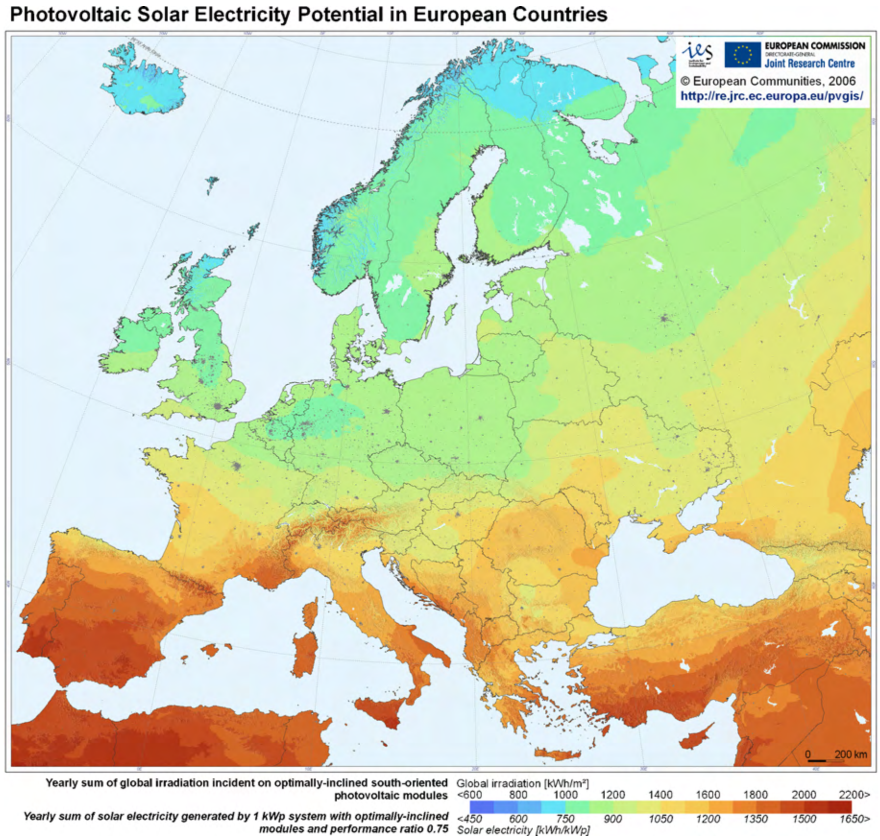

Fig. 4. Solar irradiation levels in European Countries [19].

power production ranging between 1350 and 1650 KWh per KWp can be reached [19]. Thus, there is considerable solar irradiation potential to be realised at the geographical area of interest.

However, potential application of PV technology to offshore aquaculture industry has a number of challenges to meet. In the first place these can be identified into the following:

(a) *Solar panels mounting* – solar panels have to be mounted on existing fish cages. These cages tend to be floating round flexible structures to accommodate fluctuating motion of waves. Therefore, special engineering solutions have to be devised to accommodate structural stability of solar panels and their supports.
(b) *Maintenance operations* – dealing with a constantly dynamic environment such as the sea's surface, maintenance operations have to be planned carefully and may require additional specialized equipment such as workboats, winches etc increasing the cost of the initial investment even higher.
(c) *Environmental salinity* – these systems will work in aquatic environment with considerable salinity. Consequently, PV panels have to be properly sealed to withstand such working conditions and respective support cabling to be properly strengthened. Thus, warranty related issues rise significantly in relation to traditional PV-park installations constituting operation and maintenance cost a significant burden for the aquaculture installation.
(d) *Power storage housing* – since this is a renewable energy source power takes place when solar irradiation is available, thus power storage means have to be taken into account. These power storage means, possibly an array of batteries, has to be housed in an appropriate place and engineering solutions have to be devised to meet this need. Special platforms might prove more appropriate for such an endeavour, however high costs might dictate the development of auxiliary means to be mounted on floating fish cages.
(e) *Power distribution and cabling losses* – power is to be needed in each cage. Consequently, considerable cabling is to be needed, operating in an aquatic environment, with all the risks this fact entails. In addition, cabling is expected to be exposed to solar irradiation and/or submerged into sea water hence increasing power losses need to be taken into account.
(f) *Cabling interaction with the working environment* – at an offshore aquaculture establishment considerable movements take place on a daily basis either to feed the cultured fish stock, or to monitor mooring or cage nets, or even harvest fish. Thus, connecting cabling has to avoid boat movements occurring in high frequencies on the operating plane.
(g) *Tracking systems inapplicability* – last but not least, systems enabling tracking of sun trajectory, is too difficult to be applied in an offshore aquaculture environment due to housing limitations, leading to reduced efficiency of the photovoltaic array.

4.2. Wind potential

Wind potential in Cyprus region is affected by four main parameters. According to Koroneos et al. [20] these are:

(a) Eastward moving cyclones, passing over the island;
(b) Siberian anticyclone effect coupled with the extension of the Indian monsoon low over Cyprus during summer;
(c) Large temperature differential between sea and land; and
(d) Local Mountain ranges effect, where local wind systems develop.

Fig. 5 illustrates mean annual wind speed over Cyprus region. Maximum exploitable potential is estimated to be of the region of 150–250 MW since there are some onshore areas in the

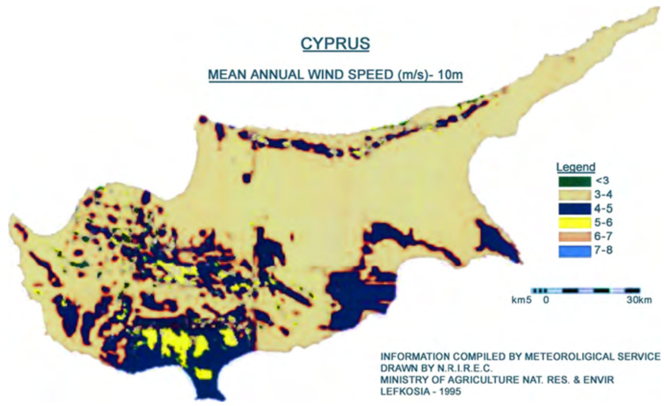

Fig. 5. Mean annual wind speed over Cyprus region [20].

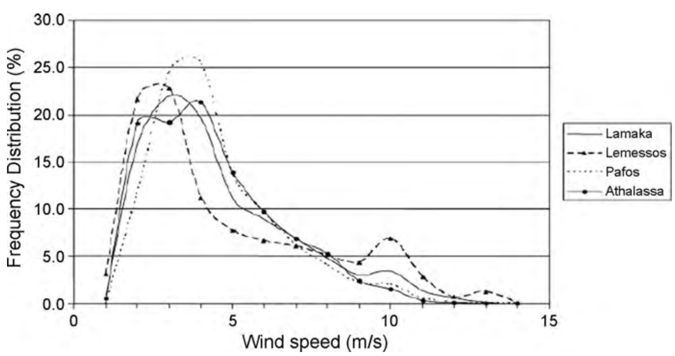

Fig. 6. Frequency distribution of wind speed in Cyprus main districts [20].

southern site of the country with mean wind velocity of 5–6 m/s and a few areas with 6.5–7 m/s as shown in Fig. 5 [20]. In particular some regions in Cyprus appear promising for wind turbines usage as shown in Fig. 6. Realisation of this potential is reflected in the construction initiation of a large wind park that will be composed by 41 wind turbines of 2 MW nominal output each. The project will cover an area of 16 Km^2 estimated to produce a total of 90 MW which comprises 27% of the total 300 MW the Republic of Cyprus has set as its 20–20–20 goals [21].

However, to the best of our knowledge no evidence exists regarding Cyprus' offshore wind potential, and in particular at Limassol's offshore coastline. A recent study carried out by the Oceanography Center at the University of Cyprus unofficially reported that at the offshore area near Vasilikos power station, outside the city of Limassol, the frequency distribution of the wind potential was 28.5% for 4–7 knots (2.05–3.60 m/s) and 27.2% for 7–11 knots (3.60–5.66 m/s) [22]. These results are promising for small offshore wind turbines utilisation since some of them require only 2.68 m/s start-up wind speeds [23]. Nevertheless, additional and more extensive research is needed to record wind potential at the area under study as to create the yearly wind profile thus providing conclusive evidence for the operational and also economic feasibility of deploying such equipment.

Similar to PV technology, potential application of wind turbines to offshore aquaculture industry has a number of challenges to meet. Most of them are similar to PV technology. An addition is structural integrity of masts supporting the small wind turbines, especially if these are not grounded on the seabed but instead are supported on the fish cages. Current operating sea depths (approximately 60–80 m) of Cyprus' offshore aquaculture establishments constitute grounding supporting wind masts on the seabed quite difficult.

4.3. Wave energy

Cyprus is an island, enjoying the benefit of been surrounded by the sea. However, similar to the offshore wind energy potential, to the best of our knowledge, no research activity has been conducted regarding the mapping and development of comprehensive wave energy potential. However, some provisional data are provided by the Cyprus Oceanography Center which offers daily and up to 60 h upfront forecasts of the offshore wave height and direction for the Cyprus' surrounding region, as shown in Fig. 7.

Meanwhile, technology for harvesting wave energy already exists although it generally lacks in maturity compared to PV and wind. Furthermore, contrasting to the obvious operating principles of the PV and wind energy converters, which are most popular, the wave energy converters are based on some innovative and not so intuitive operating principles [25]. Additionally, offshore aquaculture applications of such technology would require small devices development producing up to 150 kW constituting utilisation of existing tested technologies such as the Pelamis Wave Power project [26] out of scale and inapplicable.

4.4. Sea currents energy

Mediterranean Sea is a mid-latitude semi-enclosed sea, or an almost isolated oceanic system. Many processes which are fundamental to the general circulation of the world ocean also occur within the Mediterranean, either identically or analogously [27]. Cyprus, being close to the Levantine basin, is affected by bifurcated sub-jets coming through the Straits of Sicily. Fig. 8 illustrates a conceptual model of a jet originating from the Atlantic and how that eventually reaches Cyprus through the mid-Mediterranean jet, the Shikmona eddy and the Cretan cyclone [27].

Technology applications converting sea current potential to electricity are currently being developed. Similarly to the wave energy converters, the sea current technology is relatively new despite the fact that the first conceptual designs were presented in the mid-1970s after the first "oil crisis" [28]. Nowadays, there are many different types of sea current converters most of them taking advantage of the kinetic energy of sea currents to rotate the rotor's blades of an axial-flow or a cross-flow submerged turbine [28]. Additionally, alternative technologies also exist such as the VIVACE converter by Vortex Hydro Energy© which utilizes the vortex induced vibrations phenomena that appear on the downstream side of a bluff body in a current [29].

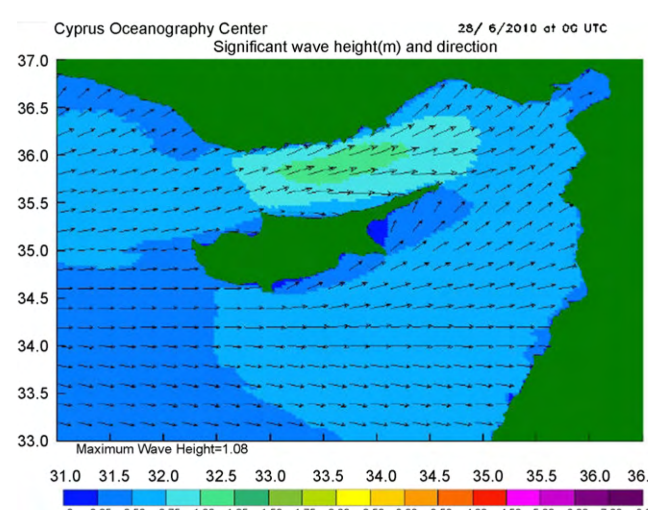

Fig. 7. Offshore wave forecasts in the Cyprus Region [24].

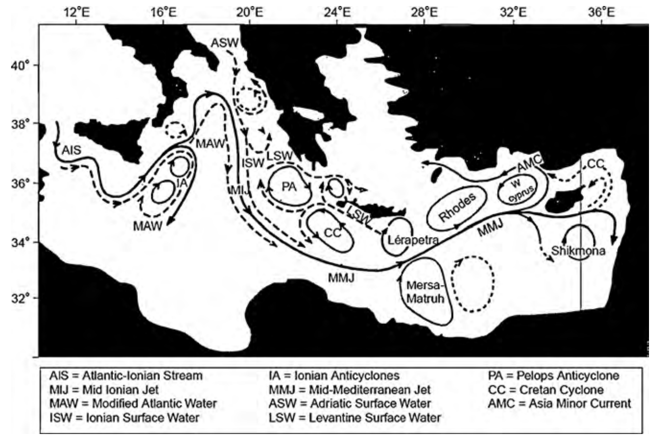

Fig. 8. A conceptual model of jet propagation [27].

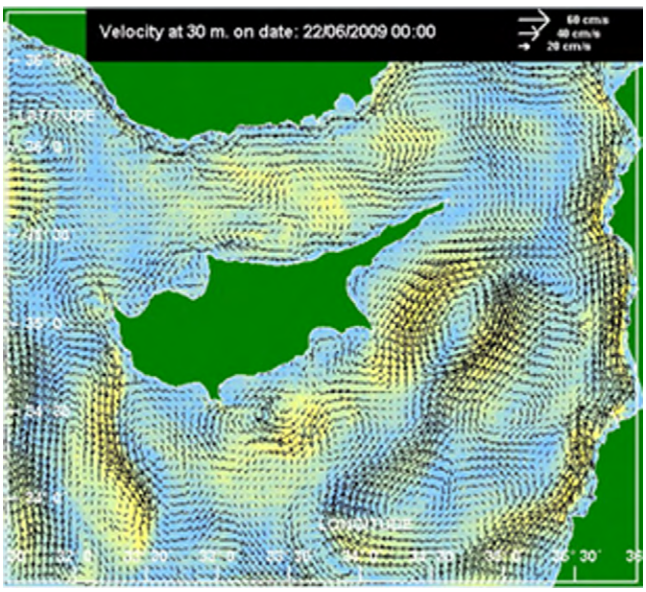

Fig. 9. Cyprus Oceanography Centre's daily current velocity release at 30 m depth [30].

Similar to Cyprus' wave profile, daily current energy profile is also monitored by the Cyprus Oceanography Center. The Center provides a five-day forecast for sea level and 30 m depth currents' velocity, shown in the following Fig. 9.

Within the context of aquaculture industry and its energy requirements further research needs to be conducted as to quantify the exact yearly energy potential at the area of interest and if it can be cost effectively exploited. Results must be correlated with existing specifications of sea current generators' in order to develop models and operational scenarios to guarantee operational adequacy of installations and tackling the economic burden of such devices deployment and maintenance.

5. Future challenges

Aquaculture economic activity is one of the most rapidly developing industries in the World. Currently, it is seen as a sustainable means of food production to satisfy World ever increasing population, provided sustainable sources of fish meal are developed. Further development of this industry requires synergistic work from multiple scientific disciplines to bear its exploration and expansion, such as marine biologists, dieticians, engineers, and many more.

Mass penetration of renewable and sustainable energy solutions to meet prospective energy needs in Mediterranean offshore aquaculture have considerable challenges. Renewable energy solutions such as PV technology or wind turbines have matured enough to be implemented, whereas wave and sea current renewable power generating technologies are in the development phase at least for such small scale applications. Additionally, mature renewable and sustainable energy solutions will have to overcome obstacles relating to their operation in an aquatic environment, as discussed at previous sections and summarized below.

As far as application of PV is concerned, some preliminary standalone system specifications must be investigated. In particular, the required autonomy days must be determined based on the energy consumption pattern of the installation despite the fact that many algorithms exist for calculating autonomy days for critical and non-critical loads; calculation of potential energy loses due to wiring and heating, bearing in mind the aquatic environment of operation; and finally, system integration design consisting of a wide variety of devices.

In addition, overall structural integrity of the mounting arrangements has to be studied and alternative engineering designs need to be developed, being able to cope with sea's dynamic loading but also provide easy access for maintenance and repairing operations. Housing requirements and mechanical design of the batteries' cases and the whole system's insulation and grounding must also be investigated. Operating in an aquatic environment, an assessment of alternative PV-cells chemical protection methods must be carried out. Last but not least, continuous movement of PV panels due to sea waves will affect the system's efficiency since the optimum panel angle and orientation would be difficult to be attained.

Provided there is satisfactory wind potential, application of small offshore wind turbines might prove less complicated compared to PV technology. During the last 20 years considerable progress has been made due to the Kyoto protocol and relating energy supplying issues [31]. Today, various technologies exist for mooring and anchoring huge masts that carry enormous wind turbines many originating from experience gained from constructing offshore oil platforms [28]. Similarly, numerous small and versatile wind turbines are commercially available suitable for offshore installations. Nevertheless, similar challenges to PV technology relating to batteries' housing and mounting methods still apply.

Whereas PV and offshore wind technologies are matured enough for "of-the-shelf" solutions, wave and sea current renewable energy technologies have considerable way to go. These technologies require further research and development of small scale solutions. In addition, further environmental data for the geographical region of interest need to be collected. Annual wave and current energy profiles generation are essential for choosing the appropriate equipment and subsequently examining the operational feasibility of the undertaking. Existing European and international research projects regarding wave and sea current technologies exceed by far the scale needed by the aquaculture industry. Development of smaller, more compact devices suitable for supplying lower power levels is still at the testing phase or in the best case scenario at the pilot stage.

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